

Inclusive jet measurements in pp and Pb–Pb collisions with ALICE

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Measurements of jet yields in heavy-ion collisions can be used to constrain jet energy loss models, and in turn provide information about the physical properties of deconfined QCD matter. ALICE reconstructs charged particle jets (*charged jets*) with high-precision tracking of charged particles down to $p_T^{\text{track}} = 150$ MeV/c, and jets (*full jets*) with the addition of particle information from the electromagnetic calorimeter down to $E_{\text{cluster}} = 300$ MeV. By including low momentum jet constituents, ALICE is uniquely positioned at the LHC to measure jets down to low jet momentum, to determine the modification to the soft components of jets, and to measure medium recoil particles. New inclusive full jet measurements in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE will be shown, over $R = 0.2 - 0.4$ and extending to low jet p_T . These will include the jet R_{AA} for different jet R , and will constitute the first such full jet measurements at low transverse jet momentum at this collision energy. The results are compared to several theoretical predictions.

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Introduction A deconfined state of Quantum Chromodynamics (QCD) is produced in ultra-relativistic heavy-ion collisions – and the study of jet modification is one of the major avenues of the heavy-ion experimental program. Jets traverse a significant pathlength of the medium, and the effect that the medium has on jets can be deduced by comparing jet properties in heavy-ion collisions to those in pp collisions. Previous measurements demonstrate suppression of the jet transverse momentum (p_T) spectrum in heavy-ion collisions, indicating that jets transfer energy to the hot QCD medium [1, 2, 3, 4]. However, the basic nature of this deconfined QCD state remains largely unknown. Jets are sensitive to a wide range of momentum exchanges with the medium, and thereby can provide insight into the medium at a wide range of resolution scales.

We report measurements of inclusive jet p_T spectra in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector [5] at the Large Hadron Collider (LHC) [6]. In pp, we report jet cross-sections for resolution parameters $R = 0.2, 0.4$ over the range $20 < p_T^{\text{jet}} < 140$ GeV/ c . In Pb–Pb, we report $R = 0.2, 0.4$ jet spectra for $40 < p_T^{\text{jet}} < 140$ GeV/ c and $60 < p_T^{\text{jet}} < 140$ GeV/ c , respectively. Jets are reconstructed in the pseudo-rapidity range $|\eta| < 0.7 - R$, and are required to contain at least one charged track with $p_T^{\text{track}} > 5 - 7$ GeV/ c (depending on the jet radius) in order to reject combinatorial jets. The jet spectra are fully corrected for detector and background effects.

Data analysis The reported Pb–Pb (pp) data were recorded by the ALICE detector at the LHC in 2015 (2017) at $\sqrt{s_{NN}} = 5.02$ TeV. We utilize a sample of 4.5M (500M) 0-10% Pb–Pb (pp) accepted minimum bias events. Jets are reconstructed with the FastJet 3.2.1 anti- k_T algorithm [7] from the combination of charged particle tracks with $p_T^{\text{track}} > 150$ MeV/ c and electromagnetic calorimeter (EMCal) clusters with $E_{\text{cluster}} > 300$ MeV. We account for the fact that charged particles deposit energy in both the tracking system and the EMCal by extrapolating tracks to the EMCal and subtracting transverse momentum from the matched clusters.

In Pb–Pb, we subtract the average background from each jet: $p_{T,\text{jet}}^{\text{reco}} = p_{T,\text{jet}}^{\text{raw}} - \rho A$, where ρ is the event-averaged background density in each event, and A is the jet area [1]. However, $p_{T,\text{jet}}^{\text{reco}}$ fails to account for fluctuations in the underlying background and a variety of detector effects, including tracking inefficiency, missing long-lived neutral particles, and material interactions. We therefore deconvolute the reconstructed jet spectrum with a response matrix describing the correlation of $p_{T,\text{jet}}^{\text{reco}}$ to the true p_T^{jet} , obtained by embedding PYTHIA 8 Monash 2013 events with the GEANT3 ALICE detector simulation into Pb–Pb data. We then employ the SVD unfolding algorithm [8] using RooUnfold [9], and correct the resulting spectrum for the kinematic efficiency and jet reconstruction efficiency.

We categorize two classes of systematic uncertainties: correlated uncertainties, which are positively correlated among all p_T^{jet} bins, and shape uncertainties, which alter the shape of the final p_T^{jet} spectrum. The dominant correlated uncertainty is the uncertainty on the tracking efficiency, and the dominant shape uncertainty is the systematic uncertainty related to the unfolding procedure.

Results The pp jet cross-sections are reported differentially in p_T and η as: $\frac{d^2\sigma_{\text{jet}}}{dp_T d\eta} = \frac{1}{\mathcal{L}} \frac{d^2N}{dp_T d\eta}$, where we experimentally measure the yield $\frac{d^2N}{dp_T d\eta}$ and the integrated luminosity \mathcal{L} [10]. The yield is corrected for the partial azimuthal acceptance of the EMCal and the vertex efficiency. Figure 1 shows the unfolded pp jet spectra for $R = 0.2$ and $R = 0.4$ jets. The jet cross-section predictions by PYTHIA 8 tune Monash 2013 are also plotted for comparison, as well as the NLO event generator

POWHEG [11], with PYTHIA 8 tune ATLAS-A14 for fragmentation. The POWHEG predictions are consistent with the measured data, while PYTHIA 8 Monash 2013 alone is not.

The Pb–Pb jet spectra are reported differentially in p_T and η as: $\frac{1}{\langle T_{AA} \rangle} \frac{1}{N_{event}} \frac{d^2 N_{jet}^{AA}}{dp_T d\eta}$, where $\langle T_{AA} \rangle \equiv \frac{\langle N_{coll} \rangle}{\sigma_{inel}^{NN}}$ is the ratio of the number of binary nucleon-nucleon collisions to the inelastic nucleon-nucleon cross-section, computed in a Glauber model to be $\langle T_{AA} \rangle = 23.4 \pm 0.78$ (sys) mb^{-1} for 0-10% centrality. Figure 2 shows the unfolded Pb–Pb full jet spectra for $R = 0.2$ and $R = 0.4$. A leading track bias of 5 GeV/c is required for the $R = 0.2$ spectra, while a 7 GeV/c bias is required for the $R = 0.4$ spectra (both pp and Pb–Pb) in order to suppress combinatorial jets in Pb–Pb.

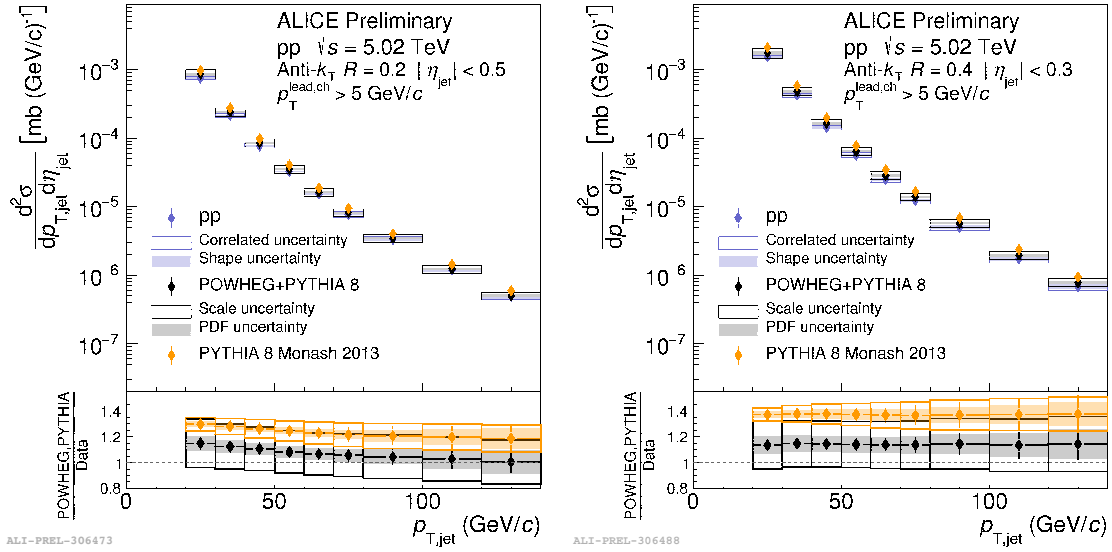


Figure 1: Unfolded pp full jet cross-sections at $\sqrt{s} = 5.02$ TeV for $R = 0.2$ (left) and $R = 0.4$ (right), along with PYTHIA 8 Monash 2013 and POWHEG+PYTHIA reference.

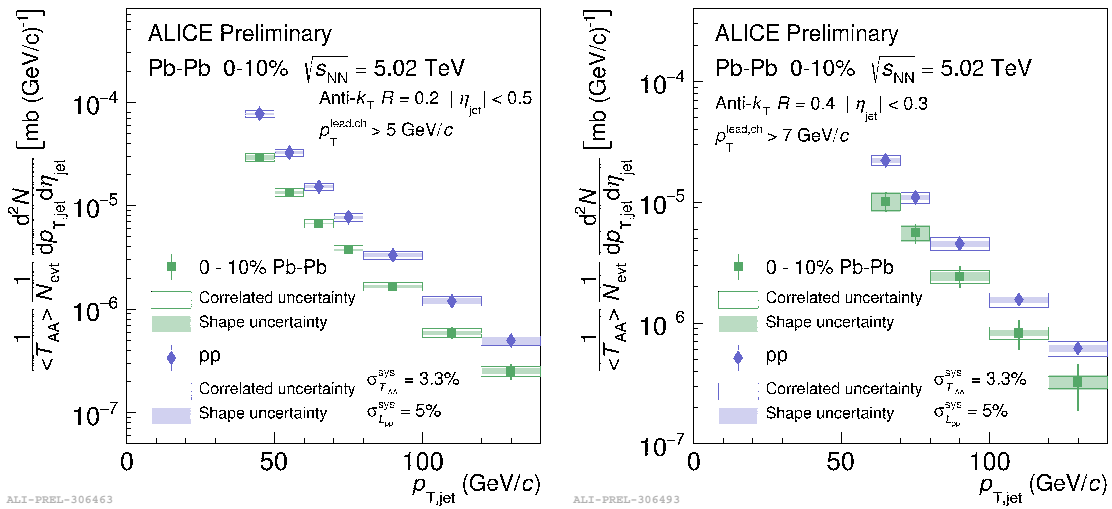


Figure 2: Unfolded pp and Pb–Pb full jet spectra at $\sqrt{s_{NN}} = 5.02$ TeV for $R = 0.2$ (left) and $R = 0.4$ (right).

The jet R_{AA} is reported as: $R_{AA} = \frac{1}{\langle T_{AA} \rangle N_{event}} \frac{d^2N}{dp_T d\eta} \Big|_{AA} / \frac{d^2\sigma}{dp_T d\eta} \Big|_{pp}$, namely the ratio of the Pb–Pb and pp spectra plotted in Fig. 2. Figure 3 shows the unfolded full jet R_{AA} for $R = 0.2$ and $R = 0.4$ jets, which exhibit strong suppression. There is visible p_T -dependence in the $R = 0.2$ case, with stronger suppression at lower p_T . There is no significant R -dependence of the jet R_{AA} within the experimental uncertainties.

We compare these results to four theoretical predictions: the Linear Boltzmann Transport (LBT) model [14, 15], Soft Collinear Effective Theory with Glauber gluons (SCET_G) [16, 17], the Hybrid model [18, 19], and JEWEL [12, 13]. The predictions are all computed using the anti- k_T jet algorithm with $|\eta| < 0.7 - R$. Leading track requirements are only applied by JEWEL (as in data) and the Hybrid model (with 5 GeV/c for both radii). All models exhibit strong suppression, and produce the same qualitative trend of R_{AA} as a function of p_T . In the case $R = 0.2$, we see that JEWEL under-predicts the jet R_{AA} , and appears to be inconsistent with the data regardless of whether medium recoils are included, while for $R = 0.4$ the “recoils on” prediction is more consistent with the data. The LBT model describes the data better, although it has slight tension with the data. Note however that neither the JEWEL nor LBT predictions include systematic uncertainties. The SCET_G predictions are fully consistent with the data, although the $R = 0.2$ prediction has large systematic uncertainties due to a lack of in-medium $\ln R$ re-summation in this calculation. Additionally, the SCET_G calculation did not include collisional energy loss, which the authors anticipate to increase the suppression for $R = 0.4$. The Hybrid model describes the trend of the data reasonably well, although like the LBT model, exhibits slight tension particularly in the $p_T < 100$ GeV/c range. It should be noted that JEWEL has not been fit to high- p_T LHC data, and so it faces the strictest test of all the models presented. While the experimental uncertainties are larger for $R = 0.4$, the model predictions span a wider range of R_{AA} than in the case of $R = 0.2$, which highlights the importance of measuring the R -dependence of the jet R_{AA} .

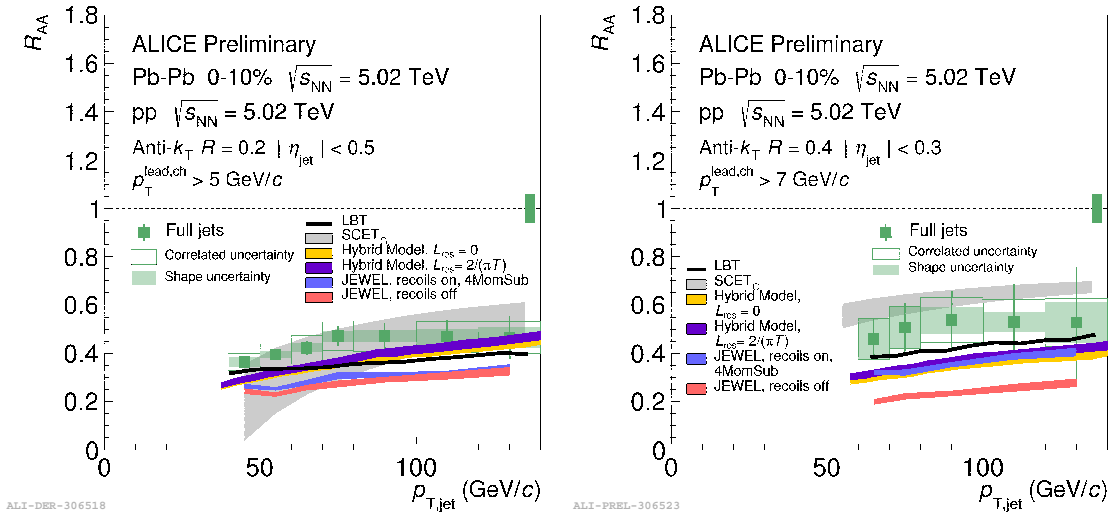


Figure 3: Jet R_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV for $R = 0.2$ (left) and $R = 0.4$ (right) compared to LBT, SCET_G, Hybrid model, and JEWEL predictions. The combined $\langle T_{AA} \rangle$ uncertainty and pp luminosity uncertainty of 6% is shown as a band on the dashed line at $R_{AA} = 1$.

Most of the models describe the R_{AA} reasonably well, but a firm quantitative conclusion remains somewhat nebulous. The predictions typically use different strategies for each of the "non jet energy loss" pieces (initial state, expansion, hadronization, pp spectrum), and do not attempt to incorporate these differences in a systematic uncertainty, which makes a strict quantitative comparison to data difficult. Moreover, the models fix their free parameters in different ways. This necessitates investigation of complementary jet observables and the need for global analyses, but it also highlights the need to standardize the ingredients of jet energy loss calculations.

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